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DEVELOPMENT OF THERMOMECHANICAL LIFE PREDICTION  
MODELS FOR THERMAL BARRIER COATINGS

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Thermal barrier coatings (TBCs) for turbine airfoils in high-performance engines represent an advanced materials technology with both performance and durability benefits. The foremost TBC benefit is the reduction of heat transferred into air-cooled components. To achieve these benefits, however, the TBC system must be reliable. Mechanistic thermomechanical and thermochemical life models and statistically significant design data are therefore required for the reliable exploitation of TBC benefits on gas turbine airfoils. Garrett's NASA-Host Program (NAS3-23945) is designed to fulfill these requirements.

This program focuses on predicting the lives of two types of strain-tolerant and oxidation-resistant TBC systems that are produced by commercial coating suppliers to the gas turbine industry. The plasma-sprayed TBC system, composed of a low-pressure plasma-spray (LPPS) applied oxidation resistant NiCrAlY bond coating and an air-plasma-sprayed yttria (8 percent) partially stabilized zirconia insulative layer, is applied by both Chromalloy (Orangeburg, New York) and Klock (Manchester, Connecticut). The second type of TBC is applied by the electron beam-physical vapor deposition (EB-PVD) process by Temescal (Berkeley, California).

Thermomechanical life models are being tailored to predict TBC strain tolerance in terms of materials (zirconia thickness, NiCrAlY roughness), engine (component temperature, applied strains) and mission (time at temperature) parameters. Continuum and fracture mechanics approaches and statistical methods are being evaluated to develop tensile and compressive strain functions required to drive a mission analysis capable thermomechanical life model for TBCs. Results of initial testing to calibrate these life models will be presented.

# GARRETT'S TBC LIFE PREDICTION STRATEGY IS COMPREHENSIVE

- COMMERCIAL FIXED-PROCESS TBC SYSTEMS
- MISSION-ANALYSIS CAPABLE LIFE MODELS
- AFFORDABLE TESTS TO CALIBRATE MODELS
- RAPID TBC LIFE COMPUTATION APPROACHES
- NDE FEASIBILITY
- ITERATIVE TFE731 TURBOFAN ENGINE TESTS TO VALIDATE LIFE ANALYSIS

Figure 1.

## LIFE PREDICTION MODELS ARE BEING DEVELOPED FOR PLASMA-SPRAYED AND EB-PVD TBC SYSTEMS

PLASMA SPRAY	ELECTRON BEAM — PHYSICAL VAPOR DEPOSITION
APS Y <sub>2</sub> O <sub>3</sub> (8%) STABILIZED ZrO <sub>2</sub>	EB-PVD Y <sub>2</sub> O <sub>3</sub> (20%) STABILIZED ZrO <sub>2</sub>
LPPS Ni-31Cr-11Al-0.5Y	EB-PVD Ni-23Co-18Cr-11Al-0.3Y
MAR-M 247 SUPERALLOY	MAR-M 247 SUPERALLOY
<ul style="list-style-type: none"> <li>• CHROMALLOY</li> <li>• KLOCK</li> </ul>	<ul style="list-style-type: none"> <li>• TEMESCAL</li> </ul>

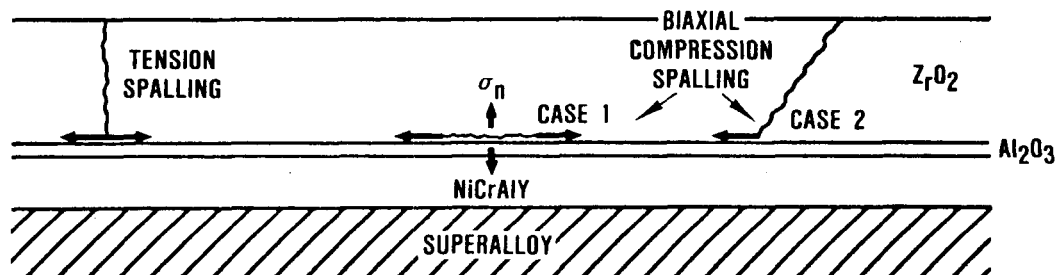
Figure 2.

# MISSION ANALYSIS CAPABLE LIFE MODELS ARE BEING DEVELOPED FOR OPERATIVE TBC FAILURE MODES

- ZIRCONIA SPALLING
- BOND COATING OXIDATION
- MOLTEN SALT FILM DAMAGE
- CARBON PARTICLE EROSION

Figure 3.

## FAILURES IN TBC ARE MECHANICALLY INDUCED



- STRESS INTENSITY AT TIP OF CRACK

$$K \sim C E \epsilon_A t^n$$

$$\epsilon_A = \epsilon_\alpha + \epsilon_T + \epsilon_R + \epsilon_C + \epsilon_S + \epsilon_{PT}$$

E = ELASTIC MODULUS

- STRAIN-TOLERANT TBC:  $E \rightarrow 0$

OXIDATION OF NiCrAlY AND ADHESION OF Al<sub>2</sub>O<sub>3</sub> SCALE  
GOVERN TBC LIFE

Figure 4.

# A MISSION ANALYSIS CAPABLE THERMOMECHANICAL MODEL PREDICTS TBC LIFE AS A FUNCTION OF ENGINE, MISSION, AND MATERIALS PARAMETERS

## CRITICAL PARAMETERS

ENGINE	MISSION	MATERIALS SYSTEM
<ul style="list-style-type: none"> <li>• COMPONENT TEMPERATURE</li> <li>• THERMAL STRAINS</li> <li>• CENTRIFUGAL STRAINS</li> <li>• TURBINE PRESSURE                             <ul style="list-style-type: none"> <li>• SALT DEPOSITION</li> </ul> </li> </ul>	<ul style="list-style-type: none"> <li>• POWER REQUIREMENTS                             <ul style="list-style-type: none"> <li>▪ LEVEL</li> <li>▪ DURATION</li> </ul> </li> <li>• ALTITUDE                             <ul style="list-style-type: none"> <li>▪ SALT DEPOSITION</li> </ul> </li> </ul>	<ul style="list-style-type: none"> <li>• <math>\epsilon_a + \epsilon_R + \epsilon_S + \epsilon_{PT}</math></li> <li>• ELASTIC MODULUS</li> <li>• <math>K_{IC}, \sigma_f</math></li> <li>• BOND COATING ROUGHNESS</li> <li>• OXIDATION RATE</li> <li>• THERMAL CONDUCTIVITY</li> <li>• THERMAL EXPANSION</li> </ul>

Figure 5.

## FRACTURE MECHANICS AND STATISTICAL APPROACHES CAN POTENTIALLY ESTABLISH SPALLING STRAIN LIMITS FOR TBCs

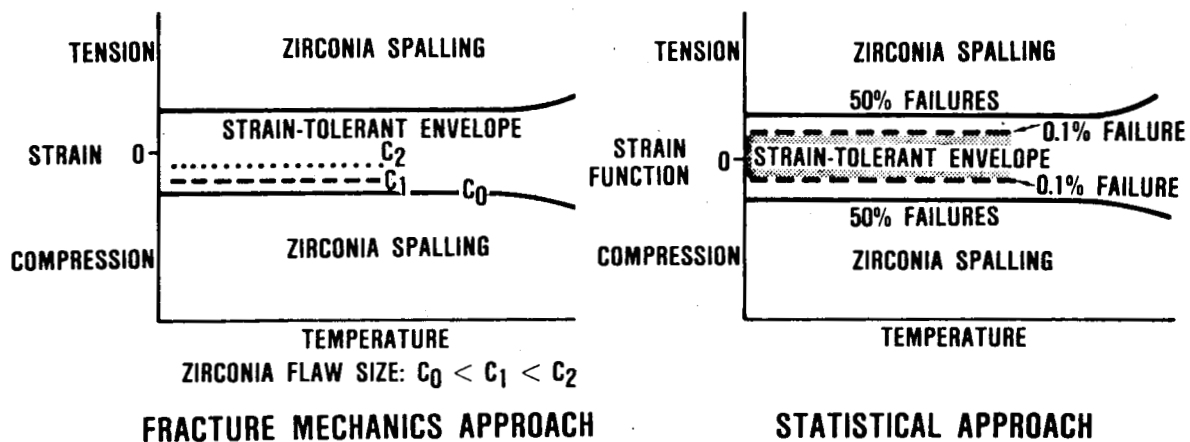
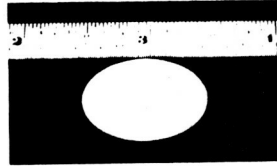


Figure 6.

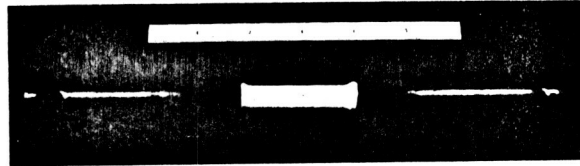
## THERMOMECHANICAL TBC LIFE MODEL IS CALIBRATED WITH AFFORDABLE TESTS

- COHESIVE (INTERFACIAL)  
STRENGTH AND TOUGHNESS



$$\sigma_f, K_{IC} = F \left\{ \begin{array}{l} \text{TEMPERATURE} \\ \text{TIME} \\ \text{NiCrAlY ROUGHNESS} \\ \epsilon_R, \epsilon_S, \epsilon_{PT} \end{array} \right.$$

- TENSILE AND COMPRESSIVE  
SPALLING STRAINS



$$\epsilon_{SPALL} = F \left\{ \begin{array}{l} \text{MODULUS} \\ \text{ZIRCONIA THICKNESS} \\ \text{TEMPERATURE} \\ K_{IC}, \sigma_f, C \\ \text{SALT DEPOSITION} \end{array} \right.$$

Figure 7.

## COHESIVE AND INTERFACIAL TOUGHNESS OF TBC SYSTEM CAN BE QUANTIFIED WITH MODIFIED BOND STRENGTH TEST

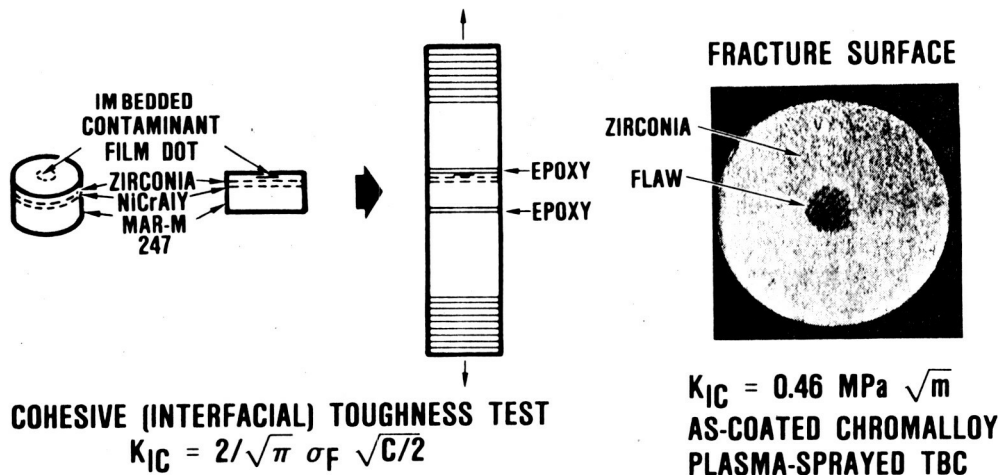


Figure 8.

## INTERFACIAL TOUGHNESS TEST IDENTIFIES MICROSTRUCTURE WEAKNESSES AND QUANTIFIES INFLUENCE OF PROCESS MODIFICATIONS

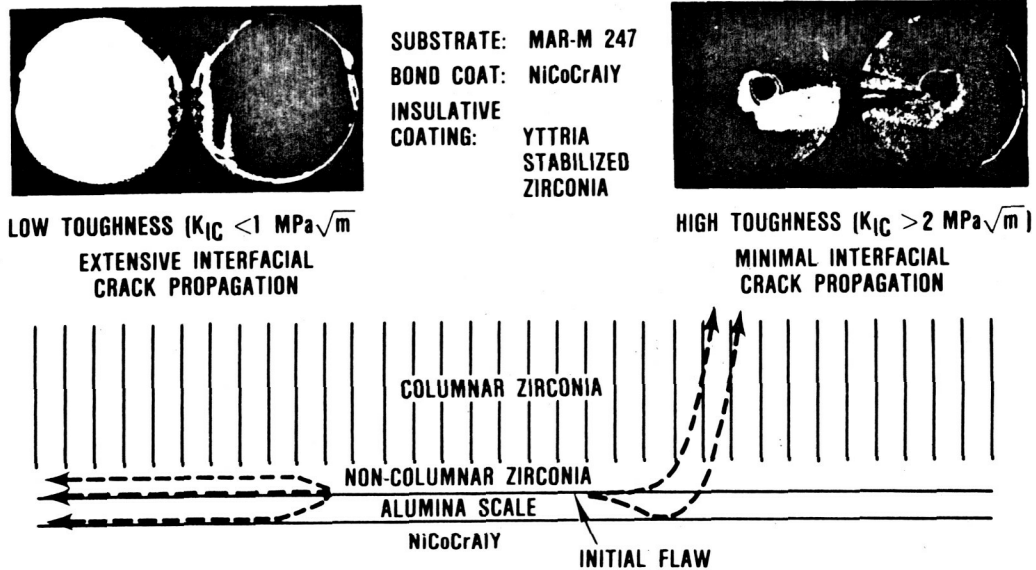


Figure 9.

## OXIDATION INDUCES SPALLING IN PLASMA-SPRAYED TBC

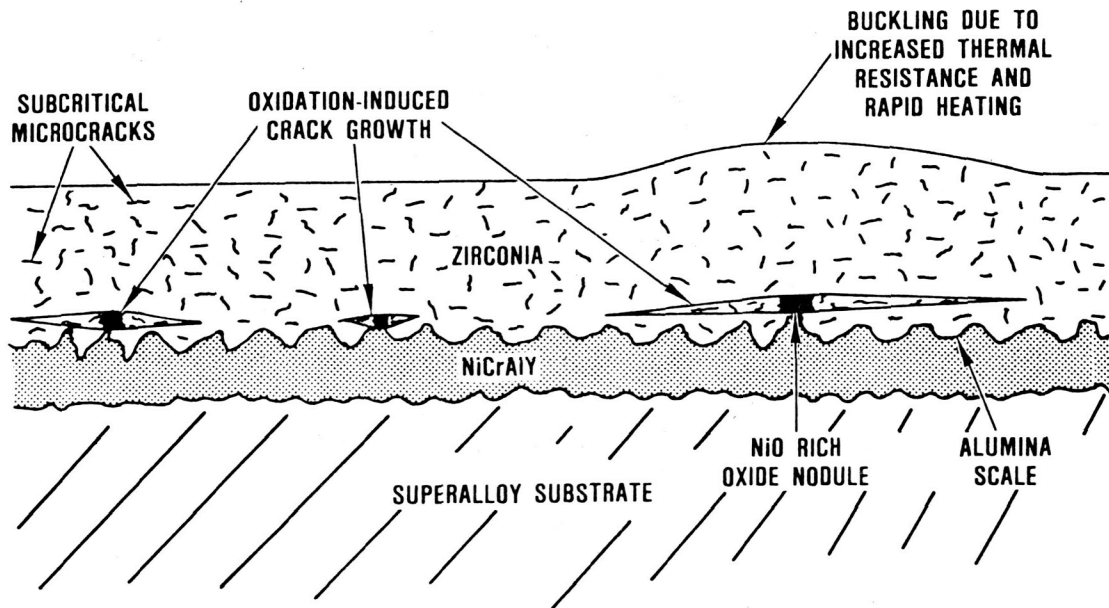


Figure 10.

# ENVIRONMENTAL FACTORS (OXIDATION AND SALT DEPOSITS) REDUCE TBC SPALLING STRAIN LIMITS

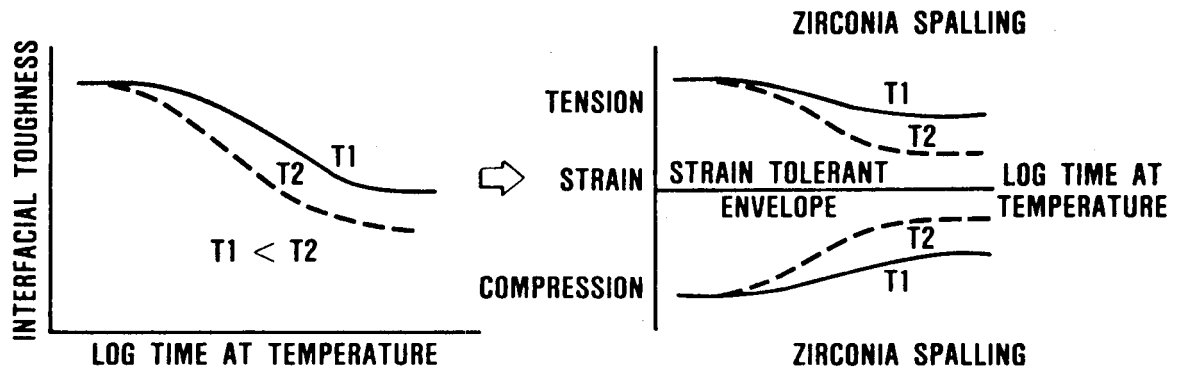


Figure 11.

## SUMMARY

- THERMOMECHANICAL MODEL IS BEING DESIGNED TO PREDICT TBC LIFE AS A FUNCTION OF ENGINE, MISSION, AND MATERIALS PARAMETERS
- LIFE MODEL IS BEING CALIBRATED FOR COMMERCIALY APPLIED PLASMA-SPRAYED (CHROMALLOY, KLOCK) AND EB-PVD (TEMESCAL) TBCs
- AFFORDABLE TESTS HAVE BEEN DEVELOPED TO CALIBRATE THERMOMECHANICAL TBC LIFE MODELS

Figure 12.